Electronic Version
Stylesheet Version v1.1.1

Description

MULTI-BEAM ANTENNA

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The instant application is a continuation-in-part of U.S. Application Serial No. 10/202,242, filed on July 23, 2002, now U.S. Patent No. 6,606,077, which is a continuation-in-part of U.S. Application Serial No. 09/716,736, filed on November 20, 2000, now U.S. Patent No. 6,424,319, which claims the benefit of U.S. Provisional Application Serial No. 60/166,231 filed on November 18, 1999, all of which are incorporated herein by reference.

BRIEF DESCRIPTION OF DRAWINGS

[0002] In the accompanying drawings:

[0003] *FIG. 1* illustrates a top view of a first embodiment of a multi-beam antenna comprising an electromagnetic lens;

[0004] *FIG. 2* illustrates a side cross-section of the embodiment of *Fig. 1*;

[0005] *FIG. 3* illustrates a side cross-section of the embodiment of *Fig. 1* incorporating a truncated electromagnetic lens;

[0006] *FIG. 4* illustrates a side cross-section of an embodiment illustrating various locations of a dielectric substrate, relative to an electromagnetic lens;

[0007] *FIG. 5* illustrates an embodiment wherein each antenna feed element is operatively coupled to a separate signal;

[0008] *FIG. 6* illustrates an embodiment wherein the switching network is separately located from the dielectric substrate;

[0009] *FIG. 7* illustrates a top view of a second embodiment of a multi-beam antenna, comprising a plurality electromagnetic lenses located proximate to one edge of a dielectric substrate;

[0010] *FIG. 8* illustrates a top view of a third embodiment of a multi-beam antenna, comprising a plurality electromagnetic lenses located proximate to opposite edges of a dielectric substrate;

[0011] *FIG. 9* illustrates a side view of the third embodiment illustrated in *Fig. 8*, further comprising a plurality of reflectors;

[0012] *FIG. 10* illustrates a fourth embodiment of a multi-beam antenna, comprising an electromagnetic lens and a reflector;

[0013] *FIG. 11* illustrates a fifth embodiment of a multi-beam antenna;

[0014] *FIG. 12* illustrates a sixth embodiment of a multi-beam antenna incorporating a first embodiment of a selective element;

[0015] *FIG. 13* illustrates an example of a frequency selective surface in accordance with the first embodiment of the selective element;

[0016] *FIG. 14* illustrates the reflectivity as a function of frequency of the frequency selective surface illustrated in *Fig. 13*;

[0017] *FIG. 15* illustrates the transmissivity as a function of frequency of the frequency selective surface illustrated in *Fig. 13*;

[0018] *FIGs. 16a* and *16b* illustrate a seventh embodiment of a multi-beam antenna incorporating a second embodiment of the selective element;

[0019] *FIG. 17* illustrates an eighth embodiment of a multi-beam antenna incorporating the second embodiment of the selective element, further incorporating a polarization rotator;

[0020] *FIG. 18* illustrates a ninth embodiment of a multi-beam antenna incorporating the first embodiment of the selective element;

[0021] *FIG. 19* illustrates a tenth embodiment of a multi-beam antenna incorporating the first embodiment of the selec-

tive element;

[0022] *FIGs. 20a,20b,20c* and *20d* illustrates an eleventh embodiment of a multi-beam antenna incorporating the first embodiment of the selective element;

[0023] *FIG. 21* illustrates a twelfth embodiment of a multi-beam antenna incorporating a curved reflective surface;

[0024] *FIG. 22* illustrates a thirteenth embodiment of a multi-beam antenna incorporating a cylindrical curved reflective surface;

[0025] *FIG. 23* illustrates a fourteenth embodiment of a multi-beam antenna incorporating a curved reflective surface having a circular cross-section in the plane of the dielectric substrate and a parabolic cross-section normal to the plane of the dielectric substrate;

[0026] *FIG. 24* illustrates a fifteenth embodiment of a multi-beam antenna incorporating a curved optical reflector, and a light source that is operatively associated with a dielectric substrate;

[0027] *FIG. 25* illustrates a sixteenth embodiment of a multi-beam antenna incorporating a cylindrical curved optical reflector, and a plurality of light sources that are operatively associated with a dielectric substrate;

[0028] *FIG. 26* illustrates a seventeenth embodiment of a multi-

beam antenna incorporating curved reflector having a circular cross-section in the plane of the dielectric substrate and a parabolic cross-section normal to the plane of the dielectric substrate, and a plurality of light sources that are operatively associated with a dielectric substrate;

[0029] *FIG. 27* illustrates a headlight assembled in vehicle; and

[0030] *FIG. 28* illustrates an exploded view of a vehicle headlight assembly.

Detailed Description

[0031] Referring to *Figs. 1* and*2*, a *multi-beam antenna 10, 10.1* comprises at least one *electromagnetic lens 12* and a plurality of *antenna feed elements 14* on a *dielectric substrate 16* proximate to a *first edge 18* thereof, wherein the plurality of *antenna feed elements 14* are adapted to radiate a respective plurality of *beams of electromagnetic energy 20* through the at least one *electromagnetic lens 12*.

[0032] The at least one *electromagnetic lens 12* has a *first side 22* having a *first contour 24* at an intersection of the *first side 22* with a *reference surface 26*, for example, a *plane 26.1*. The at least one *electromagnetic lens 12* acts to diffract the electromagnetic wave from the respective *antenna feed elements 14*, wherein different *antenna feed elements 14* at different loca-

tions and in different directions relative to the at least one *electromagnetic lens 12* generate different associated *beams of electromagnetic energy 20*. The at least one *electromagnetic lens 12* has a *refractive index n* different from free space, for example, a *refractive index n* greater than one (*1*). For example, the at least one *electromagnetic lens 12* may be constructed of a material such as Rexolite™, TEFLON™, polyethylene, or polystyrene; or a plurality of different materials having different refractive indices, for example as in a Luneburg lens. In accordance with known principles of diffraction, the shape and size of the at least one *electromagnetic lens 12*, the *refractive index n* thereof, and the relative position of the*antenna feed elements 14* to the *electromagnetic lens 12* are adapted in accordance with the radiation patterns of the *antenna feed elements 14* to provide a desired pattern of radiation of the respective *beams of electromagnetic energy 20* exiting the *second side 28* of the at least one *electromagnetic lens 12*. Whereas the at least one *electromagnetic lens 12* is illustrated as a *spherical lens 12"* in *Figs. 1* and *2*, the at least one *electromagnetic lens 12* is not limited to any one particular design, and may, for example, comprise either a spherical lens, a Luneburg lens, a spherical shell lens, a hemispherical lens, an at least partially

spherical lens, an at least partially spherical shell lens, a cylindrical lens, or a rotational lens. Moreover, one or more portions of the *electromagnetic lens 12* may be truncated for improved packaging, without significantly impacting the performance of the associated *multi-beam antenna 10, 10.1*. For example, *Fig. 3* illustrates an at least partially spherical *electromagnetic lens 12""* with opposing *first 27* and *second 29 portions* removed therefrom.

[0033] The *first edge 18* of the*dielectric substrate 16* comprises a *second contour 30* that is proximate to the *first contour 24*. The *first edge 18* of the *dielectric substrate 16* is located on the *reference surface 26*, and is positioned proximate to the *first side 22* of one of the at least one *electromagnetic lens 12*. The *dielectric substrate 16* is located relative to the *electromagnetic lens 12* so as to provide for the diffraction by the at least one *electromagnetic lens 12* necessary to form the*beams of electromagnetic energy 20*. For the example of a *multi-beam antenna 10* comprising a planar *dielectric substrate 16* located on *reference surface 26* comprising a *plane 26.1*, in combination with an *electromagnetic lens 12* having a *center 32*, for example, a *spherical lens 12"*; the *plane 26.1* may be located substantially close to the *center 32* of the *electromagnetic lens 12* so as to provide for diffraction by at least a portion of

the *electromagnetic lens 12*. Referring to *Fig. 4*, the *dielectric substrate 16* may also be displaced relative to the *center 32* of the *electromagnetic lens 12*, for example on one or the other side of the*center 32* as illustrated by *dielectric substrates 16"* and *16""*, which are located on respective *reference surfaces 26"* and *26""*.

[0034] The*dielectric substrate 16* is, for example, a material with low loss at an operating frequency, for example, DUROID™, a TEFLON™ containing material, a ceramic material, or a composite material such as an epoxy/fiberglass composite. Moreover, in one embodiment, the *dielectric substrate 16* comprises a *dielectric 16.1* of a *circuit board 34*, for example, a *printed circuit board 34.1* comprising at least one *conductive layer 36* adhered to*dielectric substrate 16*, from which the *antenna feed elements 14* and other associated *circuit traces 38* are formed, for example, by subtractive technology, for example, chemical or ion etching, or stamping; or additive techniques, for example, deposition, bonding or lamination.

[0035] The plurality of *antenna feed elements 14* are located on the *dielectric substrate 16* along the *second contour 30* of the *first edge 18*, wherein each *antenna feed element 14* comprises a least one *conductor 40* operatively connected to the *dielectric*

substrate 16. For example, at least one of the *antenna feed elements 14* comprises an *end-fire antenna element 14.1* adapted to launch or receive electromagnetic waves in a *direction 42* substantially towards or from the *first side 22* of the at least one *electromagnetic lens 12*, wherein different *end-fire antenna elements 14.1* are located at different locations along the *second contour 30* so as to launch or receive respective electromagnetic waves in different *directions 42*. An *end-fire antenna element 14.1* may, for example, comprise either a Yagi-Uda antenna, a coplanar horn antenna (also known as a tapered slot antenna), a Vivaldi antenna, a tapered dielectric rod, a slot antenna, a dipole antenna, or a helical antenna, each of which is capable of being formed on the *dielectric substrate 16*, for example, from a *printed circuit board 34.1*, for example,by subtractive technology, for example, chemical or ion etching, or stamping; or additive techniques, for example, deposition, bonding or lamination. Moreover, the *antenna feed elements 14* may be used for transmitting, receiving or both.

[0036] Referring to *Fig. 4*, the *direction 42* of the one or more *beams of electromagnetic energy 20* through the *electromagnetic lens 12, 12"* is responsive to the relative location of the *dielectric substrate 16,16"* or*16""* and the associated *reference surface*

, *26"* or *26""* relative to the *center 32* of the *electromagnetic lens 12*. For example, with the *dielectric substrate 16* substantially aligned with the *center 32*, the *directions 42* of the one or more *beams of electromagnetic energy 20* are nominally aligned with the *reference surface 26*. Alternately, with the*dielectric substrate 16"* above the *center 32* of the *electromagnetic lens 12, 12"*, the resulting one or more *beams of electromagnetic energy 20"* propagate in *directions 42"* below the *center 32*. Similarly, with the*dielectric substrate 16""* below the *center 32* of the *electromagnetic lens 12, 12"*, the resulting one or more *beams of electromagnetic energy 20""* propagate in *directions 42""* above the *center 32*.

[0037] The *multi-beam antenna 10* may further comprise at least one*transmission line 44* on the *dielectric substrate 16* operatively connected to a *feed port 46* of one of the plurality of *antenna feed elements 14* for feeding a signal to the associated *antenna feed element 14*. For example, the at least one *transmission line 44* may comprise either a stripline, a microstrip line, an inverted microstrip line, a slotline, an image line, an insulated image line, a tapped image line, a coplanar stripline, or a coplanar waveguide line formed on the*dielectric substrate 16*, for example, from a *printed circuit board 34.1*,for example, by subtractive technology, for ex-

ample, chemical or ion etching, or stamping; or additive techniques, for example, deposition, bonding or lamination.

[0038] The *multi-beam antenna 10* may further comprise a *switching network 48* having at least one *input 50* and a plurality of *outputs 52*, wherein the at least one *input 50* is operatively connected -- for example, via at least one above described*transmission line 44* -- to a *corporate antenna feed port 54*, and each *output 52* of the plurality of *outputs 52* is connected -- for example, via at least one above described *transmission line 44* -- to a respective*feed port 46* of a different *antenna feed element 14* of the plurality of *antenna feed elements 14*. The *switching network 48* further comprises at least one *control port 56* for controlling which *outputs 52* are connected to the at least one *input 50* at a given time. The *switching network 48* may, for example, comprise either a plurality of micro-mechanical switches, PIN diode switches, transistor switches, or a combination thereof, and may, for example, be operatively connected to the *dielectric substrate 16*, for example, by surface mount to an associated *conductive layer 36* of a *printed circuit board 34.1*.

[0039] In operation, a *feed signal 58* applied to the *corporate antenna feed port 54* is either blocked -- for example, by an open

circuit, by reflection or by absorption, -- or switched to the associated *feed port 46* of one or more *antenna feed elements 14*, via one or more associated *transmission lines 44*,by the *switching network 48*, responsive to a *control signal 60* applied to the *control port 56*.It should be understood that the *feed signal 58* may either comprise a single signal common to each *antenna feed element 14*, or a plurality of signals associated with different *antenna feed elements 14*. Each *antenna feed element 14* to which the *feed signal 58* is applied launches an associated electromagnetic wave into the *first side 22* of the associated *electromagnetic lens 12*, which is diffracted thereby to form an associated *beam of electromagnetic energy 20*. The associated *beams of electromagnetic energy 20* launched by different *antenna feed elements 14* propagate in different associated *directions 42*. The various *beams of electromagnetic energy 20* may be generated individually at different times so as to provided for a scanned *beam of electromagnetic energy 20*. Alternately, two or more *beams of electromagnetic energy 20* may be generated simultaneously. Moreover, different *antenna feed elements 14* may be driven by different frequencies that, for example, are either directly switched to the respective *antenna feed elements 14*, or switched via an associated *switching network 48*

having a plurality of *inputs 50*, at least some of which are each connected to different *feed signals 58*.

[0040] Referring to *Fig. 5*, the *multi-beam antenna 10,10.1* may be adapted so that the respective signals are associated with the respective*antenna feed elements 14* in a one-to-one relationship, thereby precluding the need for an associated *switching network 48*. For example, each *antenna feed element 14* can be operatively connected to an associated *signal 59* through an associated *processing element 61*. As one example, with the *multi-beam antenna 10,10.1* configured as an imaging array, the respective *antenna feed elements 14* are used to receive electromagnetic energy, and the respective *processing elements 61* comprise detectors. As another example, with the *multi-beam antenna 10,10.1* configured as a communication antenna, the respective *antenna feed elements 14* are used to both transmit and receive electromagnetic energy, and the respective *processing elements 61* comprise transmit/receive modules or transceivers.

[0041] Referring to *Fig. 6*, the *switching network 48*, if used, need not be collocated on a common *dielectric substrate 16*, but can be separately located, as, for example, may be useful for low frequency applications, for example, 1-20 GHz.

[0042] Referring to *Figs. 7, 8* and *9*, in accordance with a second

aspect, a *multi-beam antenna 10"* comprises at least a *first 12.1* and a *second 12.2 electromagnetic lens*, each having a *first side 22.1*, *22.2* with a corresponding *first contour 24.1, 24.2* at an intersection of the respective *first side 22.1*, *22.2* with the *reference surface 26*. The *dielectric substrate 16* comprises at least a *second edge 62* comprising a *third contour 64*, wherein the *second contour 30* is proximate to the *first contour 24.1* of the *first electromagnetic lens 12.1* and the *third contour 64* is proximate to the *first contour 24.2* of the *second electromagnetic lens 12.2*.

[0043] Referring to *Fig. 7*, in accordance with a second embodiment of the *multi-beam antenna 10.2*, the *second edge 62* is the same as the *first edge 18* and the *second 30* and *third 64 contours* are displaced from one another along the *first edge 18* of the *dielectric substrate 16*.

[0044] Referring to *Fig. 8*, in accordance with a third embodiment of the *multi-beam antenna 10.3*, the *second edge 62* is different from the *first edge 18*, and more particularly is opposite to the *first edge 18* of the *dielectric substrate 16*.

[0045] Referring to *Fig. 9*, in accordance with a third aspect, a *multi-beam antenna 10'''* comprises at least one *reflector 66,* wherein the *reference surface 26* intersects the at least one *reflector 66* and one of the at least one *electromagnetic lens 12*

is located between the *dielectric substrate 16* and the *reflector 66*. The at least one *reflector 66* is adapted to reflect electromagnetic energy propagated through the at least one *electromagnetic lens 12* after being generated by at least one of the plurality of *antenna feed elements 14*. A third embodiment of the *multi-beam antenna 10* comprises at least*first 66.1* and*second 66.2 reflectors* wherein the *first electromagnetic lens 12.1* is located between the *dielectric substrate 16* and the *first reflector 66.1*, the *second electromagnetic lens 12.2* is located between the *dielectric substrate 16* and the *second reflector 66.2*, the *first reflector 66.1* is adapted to reflect electromagnetic energy propagated through the *first electromagnetic lens 12.1* after being generated by at least one of the plurality of *antenna feed elements 14* on the *second contour 30*, and the *second reflector 66.2* is adapted to reflect electromagnetic energy propagated through the *second electromagnetic lens 12.2* after being generated by at least one of the plurality of *antenna feed elements 14* on the *third contour 64*. For example, the *first 66.1* and *second 66.2 reflectors* may be oriented to direct the *beams of electromagnetic energy 20* from each side in a common nominal direction, as illustrated in *Fig. 9*. Referring to *Fig. 9*, the *multi-beam antenna 10''''* as illustrated would provide for scanning in a direc-

tion normal to the plane of the illustration. If the *dielectric substrate 16* were rotated by *90* degrees with respect to the *reflectors 66.1, 66.2,* about an axis connecting the respective *electromagnetic lenses 12.1, 12.1*, then the *multi-beam antenna 10""* would provide for scanning in a direction parallel to the plane of the illustration.

[0046] Referring to *Fig. 10*, in accordance with the third aspect and a fourth embodiment, a *multi-beam antenna 10"",10.4* comprises an at least partially spherical *electromagnetic lens 12"""*, for example, a hemispherical electromagnetic lens, having a *curved surface 68* and a *boundary 70*, for example a *flat boundary 70.1*. The *multi-beam antenna 10"",10.4* further comprises a *reflector 66* proximate to the *boundary 70*, and a plurality of *antenna feed elements 14* on a *dielectric substrate 16* proximate to a *contoured edge 72* thereof, wherein each of the *antenna feed elements 14* is adapted to radiate a respective plurality of *beams of electromagnetic energy 20* into a *first sector 74* of the*electromagnetic lens 12"""*. The *electromagnetic lens 12"""* has a *first contour 24* at an intersection of the *first sector 74* with a *reference surface 26*, for example, a *plane 26.1*. The *contoured edge 72* has a*second contour 30* located on the *reference surface 26* that is proximate to the *first contour 24* of the *first sector 74*. The *multi-beam antenna 10"",10.4* fur-

ther comprises a *switching network 48* and a plurality of *transmission lines 44* operatively connected to the *antenna feed elements 14* as described hereinabove for the other embodiments.

[0047] In operation, at least one *feed signal 58* applied to a *corporate antenna feed port 54* is either blocked, or switched to the associated *feed port 46* of one or more *antenna feed elements 14*, via one or more associated *transmission lines 44*,by the *switching network 48* responsive to a *control signal 60* applied to a *control port 56* of the *switching network 48*.Each *antenna feed element 14* to which the *feed signal 58* is applied launches an associated electromagnetic wave into the *first sector 74* of the associated *electromagnetic lens 12"'''*. The electromagnetic wave propagates through -- and is diffracted by -- the *curved surface 68*, and is then reflected by the *reflector 66* proximate to the *boundary 70*, whereafter the reflected electromagnetic wave propagates through the *electromagnetic lens 12"'''* and exits -- and is diffracted by -- a *second sector 76* as an associated *beam of electromagnetic energy 20*. With the *reflector 66* substantially normal to the *reference surface 26* -- as illustrated in *Fig. 10* -- the different *beams of electromagnetic energy 20* are directed by the associated *antenna feed elements 14* in different directions

that are nominally substantially parallel to the *reference surface 26*.

[0048] Referring to *Fig. 11*, in accordance with a fourth aspect and a fifth embodiment, a *multi-beam antenna 10""",10.5* comprises an *electromagnetic lens 12* and plurality of *dielectric substrates 16*, each comprising a set of *antenna feed elements 14* and operating in accordance with the description hereinabove. Each set of *antenna feed elements 14* generates (or is capable of generating) an associated set of *beams of electromagnetic energy 20.1,20.2* and *20.3*, each having associated *directions 42.1*, *42.2* and *42.3*, responsive to the associated *feed 58* and *control 60 signals*. The associated *feed 58* and *control 60 signals* are either directly applied to the associated *switch network 48* of the respective sets of *antenna feed elements 14*, or are applied thereto through a *second switch network 78* have associated *feed 80* and *control 82 ports*, each comprising at least one associated signal. Accordingly, the *multi-beam antenna 10""",10.4* provides for transmitting or receiving one or more beams of electromagnetic energy over a three-dimensional space.

[0049] The *multi-beam antenna 10* provides for a relatively wide field-of-view, and is suitable for a variety of applications, including but not limited to automotive radar, point-

to-point communications systems and point-to-multi-point communication systems, over a wide range of frequencies for which the *antenna feed elements 14* may be designed to radiate, for example, *1* to *200 GHz*. Moreover, the *multi-beam antenna 10* may be configured for either mono-static or bi-static operation.

[0050] Referring to *Fig. 12*, in accordance with a fifth aspect and a sixth embodiment, a *multi-beam antenna 100* comprises an *electromagnetic lens 102*, at least one *first antenna feed element 104, 14*, and at least one *second antenna feed element 106, 14*. The *electromagnetic lens 102* comprises *first 108* and *second 110 portions*, wherein the at least one *first antenna feed element 104, 14* is located proximate to the *first portion 108* of the*electromagnetic lens 102*, and the at least one *second antenna feed element 106, 14* is located proximate to the *second portion 110* of the*electromagnetic lens 102*, so that the respective *feed elements 104 106, 14* cooperate with the respective *portions 108, 110* of the *electromagnetic lens 102* to which they are proximate. For example, the *electromagnetic lens 102* may comprise either a *spherical lens 102.1*, a Luneburg lens, a spherical shell lens, a hemispherical lens, an at least partially spherical lens, an at least partially spherical shell lens, a cylindrical lens, or a rotational lens divided into

first 108 and *second 110 portions*.

[0051] The *multi-beam antenna 100* further comprises a *selective element 112* located between the *first 108* and *second 110 portions* of the *electromagnetic lens 102*, wherein the *selective element 112* has a transmissivity and a reflectivity that are responsive to an electromagnetic wave property, for example either frequency or polarization. The transmissivity of the *selective element 112* is adapted so that a first electromagnetic wave, in cooperation with the *first antenna feed element 104, 14* and having a first value of the electromagnetic wave property, is substantially transmitted through the *selective element 112* so as to propagate in both the *first 108* and *second 110 portions* of the *electromagnetic lens 102*. The reflectivity of the *selective element 112* is adapted so that a second electromagnetic wave, in cooperation with the *second antenna feed element 106, 14* and having a second value of the electromagnetic wave property, is substantially reflected by the *selective element 112*. In the sixth embodiment illustrated in *Fig. 12*, the *selective element 112* is adapted with a *frequency selective surface 114* essentially a diplexer -- so that the transmissivity and reflectivity thereof are responsive to the frequency of an electromagnetic wave impinging thereon. Accordingly, a first electromagnetic wave

having a *first carrier frequency* f_1 and cooperating with the *first antenna feed element 104, 14* is transmitted, with relatively little attenuation, through the *selective element 112*, and a second electromagnetic wave having a *second carrier frequency* f_2 different from the *first carrier frequency* f_1-- and cooperating with the *second antenna feed element 106, 14* is reflected, with relatively little attenuation, by the *selective element 112*.

[0052] The *frequency selective surface 114* can be constructed by forming a periodic structure of conductive elements, e.g. by etching a conductive sheet on a substrate material having a relatively low dielectric constant, e.g. DUROID™or TEFLON™. For example, referring to *Fig. 13*, the *frequency selective surface 114* is formed by a field of what are known as *Jerusalem Crosses 116*, which provides for reflectivity and transmissivity characteristics illustrated in *Figs. 14* and *15* respectively, wherein the *frequency selective surface 114* is sized so as to substantially transmit a first electromagnetic wave having an associated *first carrier frequency* f_1 of *77* GHz, and to substantially reflect a second electromagnetic wave having an associated *first carrier frequency* f_1 of *24* GHz. In *Figs. 14* and *15*, "O"and "P"represent orthogonal and parallel polarizations respectively. Each *Jerusalem Cross*

116 is separated from a surrounding *conductive surface 118* by a *slot 120* that is etched thereinto, wherein the *slot 120* has an associated *slot width ws*. Each *Jerusalem Cross 116* comprises four*legs 122* of *leg length L* and *leg width wm* extending from a central square hub and forming a cross. Adjacent *Jerusalem Crosses 116* are separated from one another by the associated*slots 120*, and by conductive *gaps G*, so as to form a periodic structure with a *periodicity DX* in both associated directions of the *Jerusalem Crosses 116*. The exemplary embodiment illustrated in *Fig. 13* having a pass frequency of*77* GHz is characterized as follows: *slot width ws = 80* microns, *leg width wm = 200* microns, *gap G = 150* microns, *leg length L = 500* microns, and *periodicity DX = 1510* microns (in both orthogonal directions), where $DX=wm+2(L+ws)+G$. Generally the *frequency selective surface 114* comprises a periodic structure of conductive elements, for example, located on a dielectric substrate, for example, substantially located on a plane. The conductive elements need not necessarily be located on a substrate. For example, the *frequency selective surface 114* could be constructed from a conductive material with periodic holes or openings of appropriate size, shape and spacing. Alternately, the *frequency selective surface 114* may comprise

a conductive layer on one or both inner surfaces of the respective *first 108* and *second 110 portions* of the *electromagnetic lens 102*. Whereas *Fig. 13* illustrates a *Jerusalem Cross 116* as a kernel element of the associate periodic structure of the *frequency selective surface 114*, other shapes for the kernel element are also possible, for example circular, doughnut, rectangular, square, or potent cross, for example, as illustrated in the following technical papers that are incorporated herein by reference: "Antenna Design on Periodic and Aperiodic Structures"by Zhifang Li, John L. Volakis and Panos Y. Papalambros accessible at Internet address http://ode.engin.umich.edu/papers/APS2000.pdf; and "Plane Wave Diffraction by Two-Dimensional Gratings of Inductive and Capacitive Coupling Elements" by Yu. N. Kazantsev, V.P. Mal"tsev, E.S. Sokolovskaya, and A.D. Shatrov in "Journal of Radioelectronics"N. 9, 2000 accessible at Internet address http://jre.cplire.ru/jre/sep00/4/text.html.

[0053] Experiments have also shown that in a system with *first* f_1 and *second* f_2 *carrier frequencies* selected from *24* GHz and *77* GHz, an electromagnetic wave having a *24* GHz carrier frequency generates harmonic modes when passed

through the *frequency selective surface 114* illustrated in *Fig. 13*. Accordingly, the *first carrier frequency* f_1 (of the transmitted electromagnetic wave) greater than the *second carrier frequency* f_2 (of the reflected electromagnetic wave) would beneficially provide for reduced harmonic modes. However, it is possible to have a wider field of view in the transmitted electromagnetic wave than in the reflected electromagnetic wave. More particularly, the beam patterns from a reflected feed source are, for example, only well behaved over a range of approximately +/-20°, which would limit the field of view to approximately 40°. In some applications, e.g. automotive radar, it is beneficial for the lower frequency electromagnetic wave to have a wider field of view. Accordingly, it can be beneficial for the *first carrier frequency* f_1 (of the transmitted electromagnetic wave) to have the lower frequency (e.g. *24* GHz), which can be facilitated with a multiple layer *frequency selective surface 114*.

[0054] The *frequency selective surface 114* may comprise either a single layer or a multiple layer. A multiple layer *frequency selective surface 114* may provide for controlling the harmonic modes, for example, as generated by the lower frequency radiation, thereby improving the transmission of

the lower frequency radiation through the *frequency selective surface 114*, so as to provide for a wider field of view of the associated radiation pattern extending from the *electromagnetic lens 102*.

[0055] The at least one *first antenna feed element 104, 14* and at least one *second antenna feed element 106, 14* comprises respective end-fire antenna elements adapted to launch electromagnetic waves in a direction substantially towards the *first 108* and *second 110 portions* of the at least one *electromagnetic lens 102* respectively. For example, each of the respective end-fire antenna elements may be either a Yagi-Uda antenna, a coplanar horn antenna, a Vivaldi antenna, a tapered dielectric rod, a slot antenna, a dipole antenna, or a helical antenna.

[0056] The at least one *first antenna feed element 104, 14* has a corresponding at least one*first axis of principal gain 124*, which is directed through both the *first 108* and *second 110 portions* of the *electromagnetic lens 102*, and the at least one *second antenna feed element 106, 14* has a corresponding at least one *second axis of principal gain 126*, which is directed through at least the *second portion 110* of the *electromagnetic lens 102*, and the at least one *second antenna feed element 106, 14* and the *selective element 112* are adapted so that a reflec-

tion at least one *second axis of principal gain 126* from the *selective element 112* is generally aligned with at least one *first axis of principal gain 124* in the *second portion 110* of the *electromagnetic lens 102*.

[0057] Referring to *Fig. 16a*, in accordance with a seventh embodiment, a *multi-beam antenna 128* incorporates a *polarization selective element 130* for which the reflectivity or transmissivity thereof is responsive to the polarization of the electromagnetic wave impinging thereon. More particularly, one of two orthogonal polarizations is substantially transmitted by the *polarization selective element 130*, and the other of two orthogonal polarizations is substantially reflected by the *polarization selective element 130*. For example, the first electromagnetic wave associated with the *first antenna feed element 104, 14* is polarized in the y direction -- e.g. by rotating the *first antenna feed element 104, 14* relative to the *second antenna feed element 106, 14*, or by an associated antenna feed element that is orthogonally polarized with respect to the associated underlying substrate -- so as to be substantially transmitted (i.e. with relatively small attenuation) through the *polarization selective element 130*; and the second electromagnetic wave associated with the *second antenna feed element 106, 14* is polarized in the z direc-

tion so as to be substantially reflected by the *polarization selective element 130*. For example, the *polarization selective element 130* can be what is known as a polarized reflector, wherein the *second antenna feed element 106, 14* is adapted to have the same polarization as the polarized reflector. For example, a polarized reflective surface can be fabricated by etching properly dimensioned parallel metal lines at an associated proper spacing on a relatively low dielectric substrate.

[0058] Referring to *Fig. 17*, in accordance with an eighth embodiment of a multi-beam antenna*132* incorporating a *polarization selective element 130*, a *polarization rotator 134* is incorporated between the *first antenna feed element 104, 14* and the *electromagnetic lens 102* of the *electromagnetic lens 102*, for example, so that the *first 104* and second *106 antenna feed elements 14* can be constructed on a common substrate. Alternately, instead of incorporating a separate *polarization rotator 134*, the *first portion 108* of the *electromagnetic lens 102* may be adapted to incorporated an associated polarization rotator.

[0059] It should be understood that the *polarization selective element 130* and associated*second antenna feed element 106*, *14*, or*polarization rotator 134* proximate thereto, may alternately be

adapted as was the *first antenna feed element 104, 14*, or*polarization rotator 134* proximate thereto, in the embodiments of *Figs. 16a* and *17*. The resulting beam patterns for a *polarization selective element 130* would be similar to those for a *frequency selective surface 114*.

[0060] Referring to *Fig. 18*, in accordance with a ninth embodiment, a *multi-beam antenna 136* incorporates a plurality of *first antenna feed elements 104, 14* and a plurality of*second antenna feed elements 106, 14* so as to provide for multi-beam coverage by each. The plurality of *first antenna feed elements 104, 14* has an associated *first median axis of principal gain 138*, and the plurality of*second antenna feed elements 106, 14* has an associated *second median axis of principal gain 140* .

[0061] For example, by orienting the *frequency selective surface 114* at an angle $\theta = 45°$ to the intended median direction of propagation, and the plurality of*second antenna feed elements 106, 14* at an angle $\theta + \phi = 90°$, the associated second electromagnetic wave(s) can be propagated in the intended direction. By orienting the plurality of *first antenna feed elements 104, 14* on the median axis of intended propagation, the associated first electromagnetic wave(s) will propagate through the *selective element 112* along the intended direction of propagation. The particular angle θ is

not considered to be limiting. Moreover, a *polarization selective element 130* can generally operate over a relatively wide range of angles.

[0062] The pluralities of *first 104* and *second 106 antenna feed elements 106, 14* may be constructed as described hereinabove for the embodiments illustrated in *Figs. 1-5*, wherein the direction for at least one the first end-fire antenna elements is different for the direction of at least another the first end-fire antenna element, and the direction for at least one the second end-fire antenna element is different for the direction of at least another the second end-fire antenna element.

[0063] For example, the at least one *first antenna feed element 104, 14* comprises a plurality of *first antenna feed elements 104, 14* arranged substantially on a first plane, and the at least one *second antenna feed element 106, 14* comprises a plurality of *second antenna feed elements 106, 14* arranged substantially on a second plane. The first and second planes are at least substantially parallel to one another in one embodiment, and may be at least substantially coplanar so as to provide for mounting all of the *antenna feed elements 104, 106, 14* on a common substrate.

[0064] The at least one *first antenna feed element 104, 14* has a cor-

responding *first median axis of principal gain 138*, which is directed through both the *first 108* and *second 110 portion 110* of the *electromagnetic lens 102*. The at least one *second antenna feed element 106, 14* has a corresponding *second median axis of principal gain 140*, which is directed through at least the *second portion 110* of the *electromagnetic lens 102*, and the at least one *second antenna feed element 106, 14* and the *selective element 112* are adapted so that a *reflection 142* of the *second median axis of principal gain 140* from the *selective element 112* is generally aligned with the *first median axis of principal gain 138* in the *second portion 110* of the *electromagnetic lens 102*.

[0065] Referring to *Fig. 19*, in accordance with a tenth embodiment, a *multi-beam antenna 144* is adapted for improved performance, resulting in an offset angle of about 25 degrees for the *frequency selective surface 114* illustrated in *Fig. 13*, for a *first carrier frequency* f_1 of *77* GHz, and a *second carrier frequency* f_2 of *24* GHz.

[0066] Referring to *Fig. 20*, in accordance with an eleventh embodiment, a *multi-beam antenna 146* comprises a *frequency selective surface 114* oriented orthogonal to that illustrated in *Fig. 18*, wherein the associated plurality of *first antenna feed elements 104, 14* and the associated plurality of*second*

antenna feed elements 106, 14 are each orthogonal to the respective orientations illustrated in *Fig. 18*. More particularly, the plurality of *first antenna feed elements 104, 14* are oriented substantially in the y-z plane, and the plurality of *second antenna feed elements 106, 14* are oriented substantially in the x-y plane, so that the plurality of *first antenna feed elements 104, 14* and the plurality of*second antenna feed elements 106, 14* are each substantially perpendicular to the x-z plane.

[0067] The *multi-beam antenna 100* can be used to either transmit or receive electromagnetic waves. In operation, a first electromagnetic wave is transmitted or received along a first direction through an *first portion 108* of an *electromagnetic lens 102*, and a second electromagnetic wave is transmitted or received through a *second portion 110* of the *electromagnetic lens 102*. A substantial portion of the second electromagnetic wave is reflected from a *selective element 112* in a region between the *first 108* and *second 110 portions* of the *electromagnetic lens 102*. The operations of transmitting or receiving a second electromagnetic wave through a *second portion 110* of the *electromagnetic lens 102* and reflecting the second electromagnetic wave from the *selective element 112* in a region between the *first 108* and *second por-*

tions 110 of the *electromagnetic lens 102* are adapted so that both the first and second electromagnetic waves propagate along a similar median direction within the *second portion 110* of the *electromagnetic lens 102*, and the *selective element 112* transmits the first electromagnetic wave and reflects the second electromagnetic wave responsive to either a difference in carrier frequency or a difference in polarization of the first and second electromagnetic waves.

[0068] Accordingly, the *multi-beam antenna 100*, *128*, *132*, *136, 144* or *146* provides for using a common *electromagnetic lens 102* to simultaneously focus electromagnetic waves having two different carrier frequencies f_1, f_2, thereby providing for different applications without requiring separate associated apertures, thereby providing for a more compact overall package size. One particular application of the *multi-beam antenna 100*, *128*, *132*, *136, 144* or *146* is for automotive radar for which *24* GHz radiation would be used for relatively near range, wide field of view, collision avoidance applications, as well as stop and go functionality and parking aid, and *77* GHz radiation would be used for long range autonomous cruise control applications. Using the same aperture provides for substantially higher gain and

narrower beamwidths for the shorter wavelength *77* GHz radiation, hence allowing long range performance. The *24* GHz radiation would, on the other hand, present proportionally wider beamwidths and lower gain, suitable for wider field of view, shorter range applications.

[0069] Referring to *Fig. 21*, in accordance with a sixth aspect and a twelfth embodiment embodiment, a *multi-beam antenna 200* comprises a *curved reflective surface 202* and a *dielectric substrate 16* upon which are located a plurality of *antenna feed elements 14*, e.g. *end-fire antenna elements 14.1*. The *dielectric substrate 16* is located on the concave side of the *curved reflective surface 202*, and is shaped so as to provide for a cooperation of the *antenna feed elements 14* with the concave side of the *curved reflective surface 202*. The *antenna feed elements 14* are adapted to launch associate electromagnetic waves towards the concave side of the *curved reflective surface 202*, for example, substantially co-incident or aligned with a radius of curvature of the *curved reflective surface 202*. These electromagnetic waves are reflected by the*curved reflective surface 202*, which then acts similar to the *electromagnetic lens 12* of the above-described embodiments to focus the associated electromagnetic waves into associated beams, except that for the twelfth embodiment

embodiment, a *multi-beam antenna 200*, the electromagnetic waves are reflected an propagate over the *dielectric substrate 16*, whereas in the above described embodiments using an *electromagnetic lens 12*, the associated electromagnetic waves continue to propagate away from the *dielectric substrate 16* after propagating through the *electromagnetic lens 12*. Otherwise, the materials and construction of the *antenna feed elements 14* on the *dielectric substrate 16*, and the manner by which the associated signals are coupled to the *antenna feed elements 14*, is similar to that described hereinabove, particularly in conjunction with *Figs. 1* and *2*. For example, the*antenna feed elements 14* can be etched into an appropriate printed circuit material, so as to provide for launching associated electromagnetic waves off the edge of the associated substrate. For example, as illustrated in *Fig. 21*, the *antenna feed elements 14* are operatively coupled to an associated *switching network 48*, which is operatively coupled to an associated *corporate antenna feed port 54*. In the embodiment illustrated in *Fig. 21*, the *curved reflective surface 202* is substantially circular in a cross section along the intersection with a reference surface that is parallel to the *dielectric substrate 16* along the plurality of *antenna feed elements 14*.

[0070] Referring to *Fig. 22*, in accordance with a thirteenth embodiment of a *multi-beam antenna 200.1*, the *curved reflective surface 202.1* is cylindrical, so that the associated *multi-beam antenna 200.1* provides for focusing the associated electromagnetic waves along a direction parallel to the *dielectric substrate 16*, but not along a direction orthogonal thereto.

[0071] Referring to *Fig. 23*, in accordance with a fourteenth embodiment of a *multi-beam antenna 200.2*, the *curved reflective surface 202.2* has a parabolic cross-section along a direction normal to the *dielectric substrate 1*, so that the associated *multi-beam antenna 200.2* provides for focusing the associated electromagnetic waves along both a direction parallel to the *dielectric substrate 16*, and along a direction normal thereto.

[0072] Referring to *Figs. 24,25* and*26*, in accordance with a seventh aspect and associated fifteenth, sixteenth and seventeenth embodiments, the associated *multi-beam antennas 204,204.1* and*204.2* are similar to the corresponding twelfth, thirteenth and fourteenth embodiments described hereinabove, except that each is incorporated in an associated *light assembly 206, 206.1, 206.2* comprising a least one *source of light 208,208.1,208.2*, wherein the associated *curved*

reflective surfaces 202,202.1 and *202.2* function to reflect both the electromagnetic waves generated by the associated *antenna feed elements 14*, and the light generated by the a least one *source of light 208,208.1,208.2*. More particularly, the *dielectric substrate 16* is adapted so as to be operatively associated with the associated a least one *source of light 208,208.1,208.2*, e.g. the a least one *source of light 208,208.1, 208.2* may be operatively coupled thereto so as to synchronize the alignment of the a least one *source of light 208, 208.1,208.2* and the associated plurality of *antenna feed elements 14*, the combination of which can then be jointly adjusted relative to the associated at least one *curved reflective surface 202,202.1* and *202.2* so as to provide for aligning both the set of electromagnetic beams and the light beam(s).

[0073] Accordingly, the embodiments fifteenth, sixteenth and seventeenth embodiments illustrated in *Figs. 24,25* and*26* provide for a synergistic cooperation of a multi-beam electromagnetic antenna with a light source, both of which share a common *curved reflective surface 202,202.1* and *202.2*, and an associated common packaging, e.g. either open or sealed, depending upon the particular application.

[0074] For example, referring to *Figs. 27* and *28*, the *multi-beam antenna 204.2* and *light assembly 206.2* illustrated in *Fig. 26* is useful in an automotive environment, so as to provide for packaging a multi-beam radar antenna within a *headlight assembly 210*, or another light assembly, e.g. a tail light assembly (not illustrated), in the front or rear of the *vehicle 212*, respectively. The spherical/circular shape of the *curved reflective surface 202.2* in the horizontal/azimuthal direction, and parabolic shape in the vertical/elevation direction, provides for associated focusing of both the electromagnetic and optical beams in the respective directions. By packaging the *multi-beam antenna 204.2* in a *headlight assembly 210*, the alignment of the *multi-beam antenna 204.2* can be adjusted using the horizontal and vertical angular adjusters associated with the *headlight assembly 210*, e.g. without requiring a separate aligner for the *dielectric substrate 16*, thereby providing for the inherent alignment, and correction of misalignment, of the electromagnetic beams of from the*multi-beam antenna 204.2*. Co-locating the *multi-beam antenna 204.2* and *light assembly 206.2* thereby precludes the need to mount the multi-beam antenna in an otherwise disadvantageous location, e.g. in front of a radiator which could block cooling flow or limit the ac-

ceptable size of the multi-beam antenna or impose a relatively harsh thermal enviornment or within a bumper or bumper fascia which might otherwise require undesirable cutouts in associated structural or aesthetic body elements, or might otherwise adversely affect the propagation of the associated electromagnetic waves or the associated beam or sidelobe patterns. Furthermore, a typical *headlight lens 214* is constructed from a polycarbonate material which has relatively low losses at common automotive radar frequencies (e.g. 24 and 77 GHz), thereby providing a radome for the *multi-beam antenna 204.2* without substantially adversely affecting the performance of the *multi-beam antenna 204.2*.

[0075] Referring to *Fig. 26*, *first 208.1* and *second 208.2 sources of light*, e.g. incandescent or halolgen bulbs, or LED emitters, are located on either side of the *dielectric substrate 16* substantially near the parabolic focus of the associated *curved reflective surface 202.2*, so that light from the *first 208.1* and *second 208.2 sources of light* can reach both the upper and lower portions of the *curved reflective surface 202.2*, and thereby be focused in the elevation direction, while also being substantially focused in the azimuthal direction, thereby creating a light beam that is somewhat fan

shaped in azimuth and well focused in elevation. The light beam focusing could be adjusted by changing the exact placement of the *first 208.1* and *second 208.2 sources of light*. The *dielectric substrate 16* be made relatively thin (e.g. on the order of 15 mils) so as to not substantially block the associated light beam. Furthermore, millimeter wave components -- which have a relatively small cross-section -- can also be placed on the substrate without adversely affecting the light beam. Alternately, a single *source of light 208* might be located within an opening in the *dielectric substrate 16* so as to illuminate the *curved reflective surface 202.2* from both sides of the *dielectric substrate 16*.

[0076] Referring to *Figs. 27* and *28*, the *headlight assembly 210* comprises a *housing 216*, *reflector assembly 218*, *inner bezel 220* and *headlight lens 214*. In one embodiment, the *multi-beam antenna 202.2* can be integrated with one of the *headlight reflectors 218.1* (e.g. inboard) of the *reflector assembly 218*, with the remaining *headlight reflector 218.2* providing for both high and low headlight beams. Alternately, the *multi-beam antenna 204.2* can be integrated with the associated headlight in either or both of the associated *headlight reflectors 281.1*, *218.2*. Furthermore, a relatively wide field-of-view *multi-beam antenna 204.2* can be integrated with the *side*

lamp reflector 222 at a corner of the *vehicle 212*. In combination with a similar *multi-beam antenna 204.2* at the rear corner of the *vehicle 212*, this would provide for frontal, rear and side coverage.

[0077] It should be understood, that the embodiments incorporating curved reflective surfaces are not limited to the concave*curved reflective surfaces 202*, *202.1*, *202.2* described hereinabove. For example, the convex reflective surfaces can also be utilized, either alone, or in combination with other reflective surfaces, either planar or curved. For example, in the embodiment of *Fig. 1*, the *electromagnetic lens 12* could be replaced with a spherical reflective surface, which would reflect the electromagnetic waves back over the *dielectric substrate 16*. A concave curved reflective surface partially surrounding the convex curved reflective surface to then reflect the electromagnetic waves back towards the directions illustrated in *Fig. 1*, thereby providing for a multi-beam antenna embodiment that functions similar to the embodiment illustrated in *Fig. 1*, without requiring an electromagnetic lens.

[0078] While specific embodiments have been described in detail in the foregoing detailed description and illustrated in the accompanying drawings, those with ordinary skill in the

art will appreciate that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of the invention, which is to be given the full breadth of the appended claims and any and all equivalents thereof.